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(54) FORGED TURBINE BUCKET FORMED FROM STAINLESS STEEL ALLOY

(71) We, GENERAL ELECTRIC COMPANY, a corporation organized and existing under the laws of the State of New York, United States of America, of 1 River Road, Schenectady 12305, State of New York, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to a forged turbine bucket formed from a stainless steel alloy.

Stainless steel alloys containing 13% chromium are known. An article by Georg. Fischer-Aktiengesellschaft, Schaffhausen (Schweiz) and prepared for publication in the Revue de la Metallurgie, July/August 1966 relates to a high strength 13% chromium cast steel of improved weldability. The author discusses the modification of the classical 13% chromium steel to improve its weldability. His alloy composition contains —

C 0.04—0.06%

Cr 12—13%

Ni 3.5—3.9%

Mo 0.5%

The author concludes that the following cast steel composition presents undeniable advantages in comparison with the classical 13% chromium steel:

C (max.) 0.06%

Cr 12.5%

Ni 3.8%

Mo 0.5%

Another article is that of the Esco Corp. of Portland, Oregon. The article is entitled Alloy Notebook No. 13 and discloses an alloy of the composition:

C	0.08% max.
Mn	1.50% max.
Si	1.50% max.
Cr	11—14%
Ni	3.0—4.5%
Mo	1.00% max.
Fe	— Balance

However, the specific alloy that Esco apparently uses contains 13% chromium and 4% nickel and is known as Alloy 13—4.

Reference is also made to U.S. Patents 3,378,367 — Lars Eije Friis et al. and 3,385,740 — Baggstrom et al. These patents disclose steel alloys containing 11—14% chromium and 4—8% nickel. U.S. Patent 3,378,367, however, relates to steel which is martensitic in structure but contains dispersed austenite. U.S. Patent 3,385,740 discloses an austenitic-martensitic steel.

Another alloy is known which contains 11.25—13% chromium, .06 to 0.15% C and .20% molybdenum. However, the alloy contains only 0.50% nickel (max.). Such alloys are essentially the same as AISI 410 stainless steel.

The prior art states that the content of chromium can be lowered somewhat, see the article by Georg Fischer, if the carbon content is low. If silicon is present, it must be limited to prevent the formation of ferrite. If the nickel content is increased, a martensitic microstructure is obtained.

Briefly stated, the present invention relates to a forged turbine bucket formed from an alloy having a martensitic structure and free from ferrite throughout, said alloy consisting of by weight percent:

Carbon	0.05—0.07
Manganese	0.70—1.00
Silicon	0.30—0.50
Phosphorus max.	.020
Sulfur-max.	.020
Nickel	3.50—4.25
Chromium	11.20—12.25
Molybdenum	0.30—0.50
Tin	0.03 max.
Aluminum	0.03 max.
Vanadium	0.03 max.
Iron	Balance,

and wherein the yield strength of the forged product is in excess of 100,000 psi and the tensile strength is in excess of 130,000 psi.

The invention includes a method of forming a turbine bucket, which method comprises forging a turbine bucket from an alloy as defined above and heat treating the forged bucket to a yield strength level in excess of 100,000 psi and impact energy absorption properties in excess of 60 ft-lbs. as measured on a Charpy V-notch impact test.

A preferred embodiment of the invention uses an alloy containing 12% chromium, 4% nickel, and 0.05% carbon. This alloy will hereinafter be identified as

B50AH7 and forms a basis for the tests referred to hereinafter. The chromium content may be lowered and the carbon and nickel contents may be raised within the ranges specified. For example, the chromium content may be 11.2%, carbon .07%, and nickel 4.25%.

Forged turbine buckets were formed from the stainless steel forging material and were produced by the closed die forging process. The forgings were subjected to an austenitized quench and temper heat treatment which involved heating to a temperature of 1750° ± 25°F. and holding at that temperature for a minimum of two hours or 45 minutes per inch. The forgings were then quenched in oil until the surface temperature was below 212°F. and then tempered at a temperature of 1025°F. ± 25°F. for a minimum tempering time of two hours. This was followed by air cooling at room temperature. Straightening of forgings is permitted provided the straightening operation is followed by a stress relieving treatment. Stress relieving is accomplished by uniformly heating to 950° ± 25°F. and holding at that temperature for a minimum of six hours. The forgings are then air cooled to room temperature. There may be variations in the time and temperature relationship as shown in Table II, and Lots A and B, noted below.

The results of the various tests performed on forgings prepared from alloy B50AH7 are shown in the following Tables:

Heat treatments given the material before machining into test specimens are shown in Table I. Lot A followed the heat treatment and resulted in the following mechanical properties: 145 ksi tensile strength, 131.4 ksi 0.2% yield strength, 113.3 ksi 0.02% yield strength, 69.3% RA (Reduction of Area), 18.5% elongation (2 inches). Stress rupture, tensile, erosion and fatigue specimens were obtained from lot A. Stress corrosion and Goodman diagram specimens were heat treated in accordance with the alloy shown as lot B in this Table. Hardness of material so treated was R_c 31 which is approximately 144 ksi tensile strength.

TABLE I.

Heat Treatment of B50AH7

Lot A:	Austenitize		
	Oil Quench	1750°F.	2 hrs.
	Temper		
	Air Cool	1000°F.	3 hrs.
	Temper		
	Air Cool	1050°F.	5 hrs.
Lot B:	Austenitize		
	Oil Quench	1750°F.	2 hrs.
	Temper		
	Fan Quench	1025°F.	2 hrs.

The smooth stress rupture properties of B50AH7 are presented in Table II.

TABLE II.

Smooth Stress Rupture of B50AH7

Stress,** ksi	Temp. °F.	Time, hrs.	P*, $\times 10^{-3}$	El, %	R.A., %
60	850	915.6	36.62	13	76
40	950	90.2	38.00	17	79
35	950	171.3	38.39	21	84
27	975	208.0	39.19	30	90
20	1000	579.0	40.52	33	89

*P — Larson — Miller Parameter = (°F. + 459.6) (25 + log t).
**Lab Serial No. 970.

Results of elevated temperature tensile tests are presented in Table III. It is observed that strength properties decreased gradually with increasing temperature up to 800°F. above which tensile and yield strengths decreased more markedly. Ductility and Young Modulus between 75°F. and 1000°F. are also shown.

TABLE III.

Elevated Temperature Tensile Properties of B50AH7

Test Temperature, °F.	75	400	600	800	1000
T.S., ksi	136.0	125.7	119.0	109.0	84.5
0.2% Y.S., ksi	125.7	118.0	109.5	101.5	76.0
0.02% Y.S., ksi	110.8	106.5	101.7	82.0	51.0
Elong, %	21.0	18.5	17.0	17.0	22.0
R.A., %	73.3	69.7	69.3	71.9	79.3
Young's Modulus, psi $\times 10^6$	29.6	29.4	27.9	26.1	24.0

Results of cavitation erosion tests of 100 hour duration are presented in Table IV.

TABLE IV.

Cavitation Erosion

Sample	Exposure Time, hours	Weight Loss, grams
B50AH7	2	.006
R_c 32	5	.024
	11	.058
	19	.098
	40	.154
	64	.189
	89	.216
	100	.229

Estimated endurance limit with a mean stress of 70 ksi (approximately one-half of the tensile strength) was a maximum of $\pm$ 78 ksi. Individual test bar results are shown in Table V. This Goodman diagram datum point suggests that the B50AH7 alloy has high resistance to fatigue cracking even with a mean tensile stress of nearly one-half the tensile strength.

The Goodman diagram point was determined by applying a static tensile load to cylindrical specimens then rotating each specimen with an end load, giving a preselected alternating stress at the specimen gage length surface. Assuming elastic behavior, the maximum stress at the outer surface is the sum of the static tensile stress plus the alternating stress. But when this sum is greater than the yield stress, such as in the case here, the surface plastically deforms during the initial cycle. This results in a residual compressive stress on the outer surface and the actual maximum stress at the surface is reduced from the calculated stress by the amount of residual stress.

TABLE V.

Goodman Diagram Data for B50AH7

Mean Tensile Stress = 70 ksi

Sample	Alternating stress, ± ksi	Break or Runout**	Cycles × 10^{-6}
G1	47	O	15.2
G2*	57	O	17.9
G2*	77	O	10.2
G2*	97	X	.116
G3	90	X	.128
G4	81	X	.145
G5	77	O	10.4
G6	79	X	.181

*Sample G2 was step loaded.
**Break — X
Runout — O

Table VI presents the results of a staircase fatigue endurance limit determination at 800°F. The mean endurance limit was found to be ± 63.3 ksi which represents only about a 20% decrease in fatigue strength from that at room temperature. Fatigue-to-tensile strength ratio of 800°F. was determined to be 0.57. In the conventional bucket material the fatigue strength is 32% less than shown in Table VI.

TABLE VI.

800°F. Fatigue Endurance Limited of B50AH7

Sample	Alternating Stress, ksi	Break or Runout**	Cycles, × 10^{-6}
H10	60	O	10.28
H10*	65	X	9.76
H11	60	O	10.59
H12	65	O	37.93
H13	70	X	.334
H14	65	X	.632
H15	60	X	.131

*Sample H10 was step-loaded.
**Break — X
Runout — O

Bucket ZY2654, for example in Table VII, was received in a properly tempered and stress relieved condition. It was cut into Charpy Blanks and given an embrittling treatment at 870°F. for 6 hours. Impact bars were then machined and tested to determine the susceptibility of properly stress relieved B50AH7 to

subsequent embrittlement. Other portions of bucket ZY2654 were reaustenitized and tempered. Charpy Blanks were machined and reheated to 875°F. for 6 hours, furnace cooled to 650°F. then air cooled to embrittle the material. A de-embrittling treatment of 1000°F. for 2 hours followed by fan quench was given to some of the embrittled B50AH7 and the effect of the treatment measured with room temperature Charpy impact tests.

Bucket ZY2715, for example, was cut up to provide 0.505 inch gage diameter tensile bars from the mid-vane portion and from the dovetail portion. Testing was performed at room temperature. Four Charpy V notch bars were obtained from the mid-vane and four from the dovetail. The specimens were oriented axially with the notch axis perpendicular to the forging plane. Room temperature impact energy and 50% FATT (Fibrous Appearance Transition Temperature) were determined.

The tensile properties of mid-vane and dovetail are shown in Table VII. The tensile strength (137.5 ksi) and 0.2% yield strength (128 ksi) are identical in both vane and dovetail while the 0.02% yield strength of the vane, 111.8 ksi is somewhat lower than that of the dovetail, 115.5 ksi. Ductility of the dovetail was slightly greater than that of the vane, as shown in the Table. Tensile properties from both sections exceeded B50AH7 specification minimums.

TABLE VII.

Mechanical Properties of B50AH7 Production Buckets

Vendor Reports	Tensile Strength ksi	.02% Y.S., ksi	.2% Y.S., ksi	El (2") %	R.A. %	R.T. Impact Energy ft-lbs
*ZY 2602 (Samples)	138.4	116.8		20	70	93
ZY 2654 "	141.9	118.4		20	69	92
*ZY 2706 "	141.4	121.2		20	69	95
Average	140.6	118.8		20	69	93
M & P Laboratory						
ZY 2715 Dovetail (Samples)	137.5	115.5	128.0	20	67	>117
ZY 2715 Vane "	137.5	111.8	128.0	19	63	77
B50AH7 Specifiction"	130—155	100—125		15 min.	60 min.	60 min.

*Closely similar to ZY2654 with the exception of the differences recorded in this Table.

Results of the 50% FATT determinations from mid-vane and dovetail locations are given in Table VIII. Room temperature impact energy of the dovetail was greater then the vane and both were above the specification minimum. The 50% FATT of the vane, 8°F. is some 34°F. above that of the dovetail.

TABLE VIII.

Charpy V-Notch Impact of B50AH7

Location	Test Temp, °F.	Absorbed Energy ft-lbs	Fibrosity, %	50% FATT °F.
Mid-Vane	–20	22	21	+ 8
	0	40	53	
	25	34	56	
	70	77	100	
Dovetail	–40	30	31	–26
	–20	72	67	
	0	77	77	
	70	>117	100	

The longitudinal fatigue endurance limits of the vane and dovetail were found to be ± 73.5 ksi and ± 77.5 ksi, respectively. Individual test results are shown in Table IX. The fatigue-to-tensile strength ratio for both parts of the forging are above the usually assumed value of 0.5 being 0.53 in the vane and 0.56 in the dovetail.

TABLE IX.

Room Temperature Fatigue Endurance Limit of B50AH7

Dovetail			Vane		
Alternating Stress, ksi	Break or Runout*	Cycles, X10^{-6}	Alternating Stress, ksi	Break or Runout*	Cycles x 10^{-6}
70	O	10.09	70	O	10.08
75	O	10.17	75	X	1.61
80	X	.30	70	O	10.38
75	X	.88	75	O	10.01
70	O	10.38	80	X	.42
75	O	34.21	75	X	.77
80	X	1.10	70	O	11.27
75	X	1.07	75	X	.22
70	O	20.63	70	O	20.83
75	O	31.88	75	X	.66
80	X	1.82			
75	O	10.27			

TABLE IX (Continued)

Room Temperature Fatigue Endurance Limit of B50AH7

Dovetail			Vane		
Alternating Stress, ksi	**Break or Runout***	**Cycles, X10^{-6}**	**Alternating Stress, ksi**	**Break or Runout***	**Cycles x 10^{-6}**
80	O	10.02			
85	O	10.08			
90	X	.24			
85	X	1.09			

Endurance limit = ± 77.5 ksi Endurance limit = ± 73.5 ksi

*Break — X
Runout — O

The results of room temperature Charpy V-notch impact tests of embrittled B50AH7 are given in Table X. Some of the data in Table X are recorded as zero hold time. These were specimens which were heated to within 5°F. of the recorded embrittling temperature then quenched.

TABLE X.

Effect of Stress Relief Conditions on Charpy Properties of B50AH7

Temperature °F.	Hold Time hrs.	Specimen No.	Impact Energy ft-lbs	Fibrosity %	Hardness Rc
600	6	4U	49*	55	29.1
650	6	4T	57*	63	30.0
700	6	4S	51*	59	30.6
750	6	4R	53*	56	31.0
800	0	9A	82	72	29.4
800	.2	9B	103	98	30.0
800	.5	9C	68	70	29.1
800	1.8	9D	52*	56	30.5
800	6	3E1	32*	39	29.7
800	6	3E2	32*	44	29.9
800	17	9E	35*	31	30.1
825	6	3D1	54*	53	30.5
825	6	3D2	30*	40	30.8
850	6	3C1	35*	40	30.2
850	6	3C2	33*	40	29.9
875	0	4R1	102	100	30.0

TABLE X (cont.)

Temperature °F.	Hold Time hrs.	Specimen No.	Impact Energy ft-lbs	Fibrosity %	Hardness Rc
875	0	4R2	96	100	29.5
875	0	4A1	102	100	30.0
875	0	4A2	109	100	29.3
875	0	9A	72	78	20.7
875	.2	9B	69	76	30.7
875	.5	9C	68	77	30.0
875	1.7	9D	40*	53	30.4
875	6	3F3	34*	45	30.1
875	6	3F4	34*	35	30.6
875	17	9E	32*	40	30.4
900	6	3B1	37*	40	29.8
900	6	3B2	33*	35	30.0
910	6	3W	53*	53	30.2
920	6	3X	35*	44	29.3
925	0	4A	83	81	30.1
925	.2	4B	55*	62	30.1
925	.5	4C	52*	59	30.1
925	1.7	4D	39*	48	30.4
925	6	4F	45*	56	29.2
925	17	4E	89	81	29.9
930	6	3Y	53*	61	31.5
940	6	3Z	73	78	30.3
950	6	3A1	65	91	29.5
950	6	3A2	79	81	29.9
975	1.5	9M	55*	72	29.9
975	6	9N	59*	75	29.5
875	6(1)	3S1	22*	26	30.7
875	6(1)	3S2	24*	21	30.4
875	6(2)	4S1	40*	52	30.8
875	6(2)	4S2	51*	53	29.8

TABLE X (cont.)

Temperature °F.	Hold Time hrs.	Specimen No.	Impact Energy ft-lbs	Fibrosity %	Hardness Rc
1000	2(3)	4T1	101	99	29.5
1000	2(3)	4T2	99	100	29.1
1000	3(3)	4C1	109	100	29.9
1000	3(3)	4C2	95	100	28.5

(1) Furnace cooled to R.T.
(2) Furnace cooled to 650°F. then air cooled.
(3) Treatment (2) followed by deembrittlement treatment at 1000°F.
* Below B50AH7 specification minimum of 60 ft. lbs.

WHAT WE CLAIM IS:—

1. A forged turbine bucket formed from an alloy having a martensitic structure and free from ferrite throughout, said alloy consisting of by weight percent:

Carbon	.05—.07
Manganese	.70—1.00
Phosphorus	.020 max.
Sulphur	.020 max.
Silicon	.30—.50
Nickel	3.50—4.25
Chromium	11.20—12.25
Molybdenum	.30—.50
Aluminum	.03 max.
Vanadium	.03 max.
Tin	.03 max.
Iron	Remainder,

and wherein the yield strength of the forged product is in excess of 100,000 psi and tensile strength is in excess of 130,000 psi.

2. A forged turbine bucket as claimed in claim 1, wherein the chromium content of the alloy is 12%, nickel 4% and carbon 0.05%.

3. A forged turbine bucket as claimed in claim 1, wherein the chromium content of the alloy is 11.2%, carbon .07% and nickel 4.25%.

4. A method of forming a turbine bucket, which method comprises forging a turbine bucket from an alloy as defined in any one of claims 1 to 3 and heat treating the forged bucket to a yield strength level in excess of 100,000 psi and impact energy absorption properties in excess of 60 ft-lbs. as measured on a Charpy V-notch impact test.

5. A method as claimed in claim 4 substantially as hereinbefore described specifically.

6. A forged turbine bucket as claimed in claim 1 substantially as hereinbefore described specifically.

7. A forged turbine bucket when formed by a method as claimed in claim 4 or claim 5.

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